The Golden Mode for a Baryonic Z' Boson at Hadronic Colliders: $pp/p\bar{p} \to WZ' \to \ell\nu b\bar{b}$

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Abstract

Associated production of a baryonic Z' boson with the W boson can account for the excess in Wjj production observed by the CDF collaboration at the Tevatron. We analyze other possible channels of this Z' at the Tevatron and at the LHC, including $\gamma Z'$ and ZZ' with the $Z' \to jj$. We show that the chances of confirming this baryonic Z' is better at the Tevatron than at the LHC because of the faster growing backgrounds at the LHC. Unfortunately the current systematic uncertainties of the order of 10% cannot yield any significant excess in both $\gamma Z'$ and ZZ' channels at the Tevatron and also at the LHC. Nevertheless the search using the $b\bar{b}$ decay mode of Z' is much more feasible at the LHC, provided that the branching ratio $B(Z' \to b\bar{b}) > 0.1$. In particular, the $WZ' \to \ell\nu b\bar{b}$ mode has a signal-to-background ratio larger than 1. Even with 1 fb^{-1} luminosity at the LHC it can lead to a high significance level. The $WZ' \to \ell\nu b\bar{b}$ and $\gamma Z' \to \gamma b\bar{b}$ are also highly observable at the Tevatron.

I. INTRODUCTION

The recent experimental anomaly presented by the CDF collaboration was a $3.2\,\sigma$ excess in the invariant-mass window $M_{jj} \sim 120 - 160$ GeV of the dijet system of the associated production of a W boson [1]. We shall denote it by the CDF Wjj anomaly. The excess appears to be a resonance, but the current resolution [1] cannot tell whether it is a narrow resonance or not. From the distribution we can naively see that the width of the resonance appears to be slightly wider than the SM Z boson. There was a public talk [2] very recently that analyzed a larger data set of 7.3 fb^{-1}. The significance of the peak becomes more prominent and is at about 4.1σ significance level. The extension of the resonance peak shifts slightly to $130 - 170$ GeV. In the rest of this work, we estimate the SM background in this new invariant-mass window 130 GeV $< M_{jj} <$ 170 GeV and also take $M_{Z'} = 150$ GeV for illustration[1]. The CDF anomaly has stimulated a lot of phenomenological activities, where explanations can be divided into additional gauge bosons and variations [4–6], scalar bosons [7], others [8], and within the SM [9].

In a recent work [4], we proposed a baryonic Z' model to explain the anomaly. The reason for being baryonic is that if this Z' has a small leptonic branching ratio, even $O(1)\%$, it would suffer from strong constraints of the Tevatron Z' search in the dilepton mode [10]. In addition, its mixing with the SM Z boson should be extremely small to be compatible with the LEP electroweak precision data [11]. The baryonic Z' model was proposed by Barger, Cheung, and Langacker in 1996 [12] in light of the $R_b - R_c$ crisis of the LEP precision measurements at that time [13]. Theoretically many extensions of the SM have extra $U(1)$ gauge symmetries, and thus additional Z' bosons [14]. An interesting possibility is a baryonic Z' from a gauge symmetry generated by the baryon number [15]. Another possibility is kinetic mixing of the two $U(1)$'s [16] to suppress the leptonic couplings. Here we assume that the model can be embedded in an anomaly-free theory.

Since this baryonic Z' only couples with quarks, strong implications at a hadron collider is expected [12] such as a single Z' production via s-channel and the pair production processes $(W, Z, \gamma)Z'$ with $Z' \to jj$ with invariant mass M_{jj} peaked at $M_{Z'}$. The s-channel Z' production is buried under the QCD background. On the contrary the associated production with a W boson has a good chance to appear, which can explain the CDF Wjj anomaly [1].

[1] The DØ collaboration [3] just announced their result and found no evidence of such a resonance.

A natural follow-up question is what other signatures are expected at hadron colliders. Also, another question is whether the LHC with higher energies and more luminosities than the Tevatron is favorable to probe this baryonic Z' model. The first clean signature could be the excess in the Zjj and γjj channels. We show through detail analysis that it is hard to see the excess in both $\gamma Z' \to \gamma jj$ and $ZZ' \to \ell^+\ell^- jj/\nu\bar{\nu}jj$ channels at the Tevatron under the current level of systematic uncertainties and jet cuts. However, with tightened jet cuts and improved systematic uncertainties it could be promising to test the model in these two channels. We give details and show how to suppress the backgrounds. We also analyze the corresponding Wjj, Zjj, and γjj signals and backgrounds at the LHC with center-of-mass energies of $7, 10$, and 14 TeV. However, we found that these channels at the LHC are not as good as at the Tevatron, because the backgrounds are growing much faster with energy than the signals. Nevertheless, we investigate the feasibility of using $Z' \to b\bar{b}$ mode, provided that the branching ratio $B(Z' \to b\bar{b}) > 0.1$. We found that the search using $b\bar{b}$ mode would be much more promising than just the regular jets.

The organization is as follows. We briefly describe the model in Sec. II. We show in Sec. III the analysis on the Zjj and γjj channels at the Tevatron, and in Sec. IV on Wjj, Zjj, and γjj at the LHC. We study $\gamma b\bar{b}$, $Zb\bar{b}$, and $Wb\bar{b}$ at the LHC and at the Tevatron in Sec. V. We summarize in Sec. VI.

II. BARYONIC Z' MODEL

Following Ref. [17], we consider the Lagrangian describing the neutral current gauge interactions of the standard electroweak $SU(2) \times U(1)$ and extra $U(1)$'s, given by

$$-\mathcal{L}_{\rm NC} = eJ^{\mu}_{\rm em}A_{\mu} + \sum_{\alpha=1}^{n} g_{\alpha} J^{\mu}_{\alpha} Z^0_{\alpha\mu} \,, \tag{1}$$

where Z^0_1 is the SM Z boson and Z^0_α with $\alpha \geq 2$ are the extra Z bosons in the weak-eigenstate basis. For the present work we only consider one extra Z^0_2 mixed with the SM Z^0_1 boson. The coupling constant g_1 is the SM coupling $g/\cos\theta_{\rm w}$ where $\theta_{\rm w}$ is the weak mixing angle. In grand unified theories g_2/g_1 is

$$\frac{g_2}{g_1} = \left(\frac{5}{3}\sin^2\theta_{\rm w}\lambda\right)^{1/2} \simeq 0.62\lambda^{1/2} \,, \tag{2}$$

where the factor $\lambda \sim O(1)$ depends on the symmetry breaking pattern and the fermion sector of the theory.

Since we only consider one additional Z_2^0 we can rewrite the Lagrangian with only the Z_1^0 and Z_2^0 interactions:

$$-\mathcal{L}_{Z_1^0 Z_2^0} = \frac{g_1}{2} Z_{1\mu}^0 \left[\sum_i \bar{\psi}_i \gamma^\mu (g_v^{i(1)} - g_a^{i(1)} \gamma^5) \psi_i \right] + \frac{g_2}{2} Z_{2\mu}^0 \left[\sum_i \bar{\psi}_i \gamma^\mu (g_v^{i(2)} - g_a^{i(2)} \gamma^5) \psi_i \right] . \quad (3)$$

For both SM quarks and leptons

$$g_v^{i(1)} = T_{3L}^i - 2x_{\rm w} Q_i \,, \qquad g_a^{i(1)} = T_{3L}^i \,, \quad (4)$$

where T_{3L}^i and Q_i are, respectively, the third component of the weak isospin and the electric charge of the fermion i. We consider the case in which Z_2^0 couples only to quarks:

$$g_v^{q(2)} = \epsilon_V \,, \qquad g_a^{q(2)} = \epsilon_A \,, \qquad g_v^{\ell(2)} = g_a^{\ell(2)} = 0 \,. \quad (5)$$

The parameters ϵ_V and ϵ_A are the vector and axial-vector couplings of Z_2^0. Without loss of generality we choose $\epsilon_V = \sin\gamma$ and $\epsilon_A = \cos\gamma$ such that $(\epsilon_V^2 + \epsilon_A^2)$ is normalized to unity:

$$\left(g_v^{q(2)}\right)^2 + \left(g_a^{q(2)}\right)^2 = \epsilon_V^2 + \epsilon_A^2 = 1. \quad (6)$$

The mixing of the weak eigenstates Z_1^0 and Z_2^0 to form mass eigenstates Z and Z' are parametrized by a mixing angle θ:

$$\begin{pmatrix} Z \\ Z' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} Z_1^0 \\ Z_2^0 \end{pmatrix} . \quad (7)$$

After substituting the interactions of the mass eigenstates Z and Z' with fermions are

$$-\mathcal{L}_{ZZ'} = \sum_i \frac{g_1}{2} \left[Z_\mu \bar{\psi}_i \gamma^\mu (v_i - a_i \gamma^5) \psi_i + Z'_\mu \bar{\psi}_i \gamma^\mu (v'_i - a'_i \gamma^5) \psi_i \right] , \quad (8)$$

where

$$v_i = g_v^{i(1)} + \frac{g_2}{g_1} \theta \, g_v^{i(2)} \,, \qquad a_i = g_a^{i(1)} + \frac{g_2}{g_1} \theta \, g_a^{i(2)} \,, \quad (9)$$

$$v'_i = \frac{g_2}{g_1} g_v^{i(2)} - \theta \, g_v^{i(1)} \,, \qquad a'_i = \frac{g_2}{g_1} g_a^{i(2)} - \theta \, g_a^{i(1)} \,. \quad (10)$$

Here we have used the valid approximation $\cos\theta \approx 1$ and $\sin\theta \approx \theta$. In the following, we ignore the mixing ($\theta = 0$) such that the precision measurements for the SM Z boson are not affected, unless stated otherwise. For later discussions, we also express couplings of the Z' boson as

$$-\mathcal{L}_{Z'} = g_2 Z'_\mu \sum_i \bar{\psi}_i \gamma^\mu (g'_{iL} P_L + g'_{iR} P_R) \psi_i \quad (11)$$

where the left- and right-handed couplings are given by $g'_{iL,iR} = (g_v^{i(2)} \pm g_a^{i(2)})/2$ in the limit of no Z-Z' mixing.

The decay width of $Z' \to q\bar{q}$ is given by

$$\Gamma(Z' \to q\bar{q}) = \frac{G_F M_Z^2}{6\pi\sqrt{2}} N_c C(M_{Z'}^2) M_{Z'} \sqrt{1-4x} \left[\left(v'_q\right)^2 (1+2x) + \left(a'_q\right)^2 (1-4x) \right] , \tag{12}$$

where G_F is the Fermi coupling constant, $C(M_{Z'}^2) = 1 + \alpha_s/\pi + 1.409(\alpha_s/\pi)^2 - 12.77(\alpha_s/\pi)^3$, $\alpha_s = \alpha_s(M_{Z'})$ is the strong coupling at the scale $M_{Z'}$, $x = m_f^2/M_{Z'}^2$, and $N_c = 3$ or 1 if f is a quark or a lepton, respectively. The Z' width is proportional to λ, which sets the strength of the Z' coupling. For $\lambda = 1$ the total Z' width is

$$\frac{\Gamma_{Z'}}{M_{Z'}} = 0.022 \quad \text{for } M_{Z'} < 2m_t \ . \tag{13}$$

The width would be increased somewhat if there are open channels for decay into the top quark, superpartners, and other exotic particles. Essentially, it is a narrow resonance.

III. UA2 CONSTRAINT AND FIT TO THE CDF Wjj EXCESS

The dominant production of the Z' boson at a hadron collider is through the $q\bar{q} \to Z'$ subprocess with the cross section in the narrow Z' width approximation of [18]

$$\hat{\sigma}(q\bar{q} \to Z') = K \frac{2\pi}{3} \frac{G_F M_Z^2}{\sqrt{2}} \left[\left(v'_q\right)^2 + \left(a'_q\right)^2 \right] \delta\left(\hat{s} - M_{Z'}^2\right) \ . \tag{14}$$

The K-factor represents the enhancement from higher order QCD processes, estimated to be $K = 1 + \frac{\alpha_s(M_{Z'}^2)}{2\pi} \frac{4}{3} \left(1 + \frac{4}{3}\pi^2\right) \simeq 1.3$ [18]. When the mixing is ignored, we have

$$\left(v'_q\right)^2 + \left(a'_q\right)^2 = (0.62)^2 \lambda \tag{15}$$

and the cross section is independent of the parameter γ as long as $\epsilon_V^2 + \epsilon_A^2 = 1$.

Note that all the current and previous dijet-mass searches [19] at the Tevatron are limited to $M_{jj} > 200$ GeV, which are not applicable to the present Z' with $M_{Z'} \approx 145-150$ GeV. The relevant dijet data were from UA2 collaboration with collision energy at $\sqrt{s} = 630$ GeV. The UA2 collaboration detected the $W + Z$ signal in the dijet mass region $48 < M_{jj} < 138$ GeV and put upper bounds on $\sigma B(Z' \to jj)$ over the range $80 < M_{jj} < 320$ GeV [20]. The analysis on the UA2 data were shown in Fig. 1 of Ref. [12]: the allowed values are $\lambda \lesssim 1$ for $M_{Z'} = 100 - 180$ GeV, given the uncertainty in the K-factor in the theoretical cross

section calculation and the difficulty in obtaining an experimental bound by subtraction of a smooth background. Under the assumption that Z' coupling to the up-type quark is the same as that to the down-type quark, the UA2 constraint is therefore given by

$$\text{UA2 constraint: } \lambda < 1. \tag{16}$$

Our phenomenological model does not specify each Z' coupling, g'_{iL} and g'_{iR}. The single production of Z' in Eq. (14) does not depend on the relative size of g'_{iL} to g'_{iR} as long as the normalization of $(g'_{iL})^2 + (g'_{iR})^2 = 1/2$ holds. Note that the production of $\gamma Z'$ is also proportional to $(g'_{iL})^2 + (g'_{iR})^2$ because of the vector coupling of the photon with fermions. On the contrary, the production of WZ', which may explain the CDF Wjj anomaly, only depends on the left-handed coupling because of the presence of the W boson.

In Ref. [4], we have assumed the democratic coupling of Z', and chosen $\epsilon_V = \epsilon_A = 1/\sqrt{2}$, or equivalently

$$g'_{iL} = \frac{1}{\sqrt{2}}, \qquad g'_{iR} = 0\ . \tag{17}$$

Note that the purely left-handed coupling for the Z' boson maximizes $\sigma(WZ' \to Wjj)$ with a given value of λ. Together with the choice of $\lambda = 1$, which is maximally allowed by the UA2 data, we could explain the cross section of $\sigma(WZ') = 4$ pb claimed by CDF [1]. The relative size of g'_{iL}/g'_{iR} can have some other combinations if the excess in the CDF data is estimated differently, *e.g.*, $2.5 - 4$ pb as suggested in some of the papers [5]. If we set $\sigma(WZ') = 3$ pb and $\lambda = 1$, we have $g_L^{i(2)} = \frac{1}{\sqrt{2}}\frac{\sqrt{3}}{2}$ and $g_R^{i(2)} = \frac{1}{\sqrt{2}}\frac{1}{2}$. Finally the other channel ZZ', which was shown in Ref. [6], depends dominantly on the left-handed coupling: at the LHC this dominance becomes more significant. In order to maximize the production of ZZ' and WZ' under the UA2 constraint, the choice of couplings is now clear to be in Eq. (17). In the rest of the paper, we shall stick to this choice.

IV. WZ', ZZ' AND $\gamma Z'$ PRODUCTION AT THE TEVATRON

The associated production of Z' with a W boson goes through the t- and u-channel exchange of quarks. The s-channel W boson exchange is highly suppressed because of the negligible mixing angle between the SM Z boson and the Z'. Consequently, we expect similar or even larger cross sections for $M_{Z'} \sim M_Z$ than the SM WZ production in which there is a delicate gauge cancellation among the t-, u-, and s-channel diagrams. The cross section at

the Tevatron energy $\sqrt{s} = 1.96$ TeV is about 4 pb for $\lambda = 1$ and the normalized Z' coupling in Eq. (17). We have included a K-factor of $K = 1.3$ to approximate next-to-leading order QCD contributions [21].

As shown in Ref. [12] other associated production channels, $\gamma Z'$, ZZ', and $Z'Z'$ are possibly observable, provided that the current excess is due to WZ' production. With the same parameters, we have $\sigma(ZZ') \simeq 1.3$ pb, $\sigma(\gamma Z') \simeq 0.7$ pb, and $\sigma(Z'Z') \simeq 0.4$ pb for $M_{Z'} = 145$ GeV. For the acceptance on the final state photon, we have imposed $p_T(\gamma) >$ 50 GeV and $|\eta(\gamma)| < 1.1$ [22]. Simply from the signal cross sections, one may tempt to conclude that the WZ' channel is the most likely one to be observed, followed by ZZ' and $\gamma Z'$. However, one cannot easily draw this conclusion without working out the corresponding backgrounds. The same is also true to the LHC. In fact, we shall show in the next section that the backgrounds grow faster than the signals such that the situation at the LHC is no better than that at the Tevatron.

The irreducible backgrounds to the $(\gamma, W, Z)Z'$ signals with $Z' \to jj$ arise from the $(\gamma, W, Z)jj$ final states. We calculate the backgrounds using the MADGRAPH package [23]. It was mentioned in Refs. [1, 24] and in Ref. [25] that no significant excess is observed in Zjj and γjj channel, respectively. We shall show that with current systematic uncertainties of level 10% [1, 24–26] and a similar set of jet cuts, no significant excess can be observed in both channels. Some improvements are possible if we further tighten the cuts on the jets. Details of the signal and background cross sections are summarized in Table I. Here we have used an integrated luminosity of 10 fb^{-1} in deriving the significance.

The initial choice for jet cuts is the same as the jet cuts in Ref. [1]:

$$\begin{aligned} &E_{Tj} > 30 \text{ GeV}, \quad |\eta_j| < 2.4, \quad p_{Tjj} > 40 \text{ GeV} , \\ &130 \text{ GeV} < M_{jj} < 170 \text{ GeV} . \end{aligned} \tag{18}$$

Leptonic cuts for $Z \to \ell^+\ell^-$ are

$$p_{T\ell} > 25 \text{ GeV}, \quad |\eta_\ell| < 2.8 , \tag{19}$$

and the photon cuts are

$$p_T(\gamma) > 50 \text{ GeV} , \quad |\eta(\gamma)| < 1.1 . \tag{20}$$

In order to understand the lack of the excess in the γjj and Zjj yet, we first discuss these two channels with data for $\mathcal{L} = 4.3\,\text{fb}^{-1}$. For the Zjj channel we have $\sigma_{\text{signal}} : \sigma_{\text{bkgd}} =$

26 fb : 150 fb. It would give a significance of $S/(\sqrt{B} \oplus 0.1B) \approx 1.5\sigma$, where the factor 0.1 is the systematic uncertainties. With the same set of jet cuts and photon cuts in Eq. (20) to the γjj channel, we obtain $\sigma_{\rm signal} : \sigma_{\rm bkgd} = 0.5\,{\rm pb} : 8.8\,{\rm pb}$, which gives a significance of $S/(\sqrt{B}\oplus 0.1B) \approx 0.5\sigma$. Therefore, we cannot observe any significant excess in both channels at the Tevatron, in accord with the claims in Refs. [1, 25].

Nevertheless, if we tighten the jet cuts the backgrounds will suffer more than the signals. With

$$
\begin{aligned}
&E_{Tj} > 50\,{\rm GeV}, \quad |\eta_j| < 2.4, \quad p_{Tjj} > 40 \text{ GeV} , \\
&130 \text{ GeV} < M_{jj} < 170 \text{ GeV}
\end{aligned}
\tag{21}
$$

and $\mathcal{L} = 10\,{\rm fb}^{-1}$, the significance can improve to 2.4σ and 1σ for Zjj and γjj channel, respectively. If the systematic uncertainties can be reduced to an ideal level of $2-3\%$ the significance can be further improved to 5σ and 4σ, respectively. Details of the signal and background cross sections are summarized in Table I.

In Table I, we also include the channel $ZZ' \to \nu\bar{\nu}jj$, where we have imposed a transverse missing energy cut $\not{E}_T > 40$ GeV. Though it may have larger background, it enjoys a larger branching ratio of $B(Z \to \nu\bar{\nu})$. Experimentally, one can combine both the leptonic and invisible modes in the search to increase the event rates.

Note that our method to estimate the significance is very basic simply by taking the systematic and statistical uncertainties as independent quantities and adding them in quadrature. The information on the current systematic uncertainties were gathered in a number of CDF papers [1, 19, 25] and the thesis in Ref. [26]. The dijet systematic uncertainties in the signal region are all about 10%. The significance presented here can only be compared to one another in the relative sense. The one presented in the CDF paper [1] was based on the true data and through detailed background studies. In order to achieve a significance of about 3σ in the Wjj channel, we need a systematic uncertainty of $5-6\%$ in our basic quadrature method, shown in the second last row of Table I.

Brief comments on the dominance of the systematic uncertainties are in order here. With about a 1 pb cross section for a total 10 fb^{-1} luminosity, we have about 10^4 events. The 10% systematic uncertainty ($\sim 10^3$ events) is much larger than the statistical uncertainty ($\sim 10^2$ events). Unless there is significant improvement of systematic uncertainty, a larger data set does not help to improve our signal since the significance in this case is mainly

TABLE I. Signal and background cross sections for $\gamma Z' \to \gamma jj$, $ZZ' \to \ell^+\ell^- jj$, $ZZ' \to \nu\bar{\nu}jj$, and $WZ' \to \ell\nu jj$ at the Tevatron for $M_{Z'} = 150$ GeV, with jet cuts defined in Eqs. (18) and (21). Photons cuts for γjj are in Eq. (20), the lepton cuts for $Zjj \to \ell^+\ell^- jj$ are in Eq. (19), and the leptonic cuts for $Wjj \to \ell\nu jj$ are $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 1$, and $\not{E}_T > 25$ GeV. Significance levels are calculated with 10%, 6%, and 2% systematic uncertainty, shown in the last three columns, respectively, with $\mathcal{L} = 10$ fb^{-1},

Jet cuts (Tevatron)	σ_{signal}	σ_{bkgd}	$\frac{S}{\sqrt{B}\oplus 0.1B}$	$\frac{S}{\sqrt{B}\oplus 0.06B}$	$\frac{S}{\sqrt{B}\oplus 0.02B}$
	$\gamma Z' \to \gamma jj$				
$E_{Tj} > 30$ GeV	0.49 pb	8.79 pb	0.55	0.92	2.7
$E_{Tj} > 50$ GeV	0.28 pb	3.05 pb	0.91	1.5	4.4
	$ZZ' \to \ell^+\ell^- jj$ ($\ell = e, \mu$)				
$E_{Tj} > 30$ GeV	0.026 pb	0.15 pb	1.7	2.6	5.3
$E_{Tj} > 50$ GeV	0.015 pb	0.057 pb	2.4	3.6	5.7
	$ZZ' \to \nu\bar{\nu}jj$ ($\nu = \nu_e, \nu_\mu, \nu_\tau$) with $\not{E}_T > 40$ GeV				
$E_{Tj} > 30$ GeV	0.12 pb	0.80 pb	1.5	2.5	6.8
$E_{Tj} > 50$ GeV	0.072 pb	0.30 pb	2.4	3.8	8.8
	$WZ' \to \ell\nu jj$ ($\ell = e, \mu$)				
$E_{Tj} > 30$ GeV	0.16 pb	0.92 pb	1.8	2.9 (5%: 3.5)	7.9
$E_{Tj} > 50$ GeV	0.096 pb	0.35 pb	2.7	4.4 (5%: 5.2)	10.4

proportional to S/B. However, we expect that a larger data set would help us understand the background better, and thus reduce the systematic uncertainties.

V. Wjj, Zjj, AND γjj CHANNELS AT THE LHC

For the SM backgrounds at the LHC, the jet cuts are chosen as

$$E_{Tj} > 50\,\text{GeV}, \quad |\eta_j| < 2.5, \quad p_{Tjj} > 40\text{ GeV}\,,$$
$$130\text{ GeV} < M_{jj} < 170\text{ GeV}\,. \tag{22}$$

The cuts on the final-state photon are

$$p_T(\gamma) > 50\text{ GeV}, \quad |\eta(\gamma)| < 2.0. \tag{23}$$

The cuts on the final-state charged leptons (electrons and muons) are

$$p_{T\ell} > 25 \text{ GeV}, \quad |\eta_\ell| < 2.5 \; . \tag{24}$$

We use the same leptonic cuts for the $Z \to \ell^+\ell^-$ and $W^\pm \to \ell^\pm \nu_\ell$, and additional energy missing cut in the W decay:

$$\not{E}_T > 40 \text{ GeV} \; . \tag{25}$$

We show the cross sections and significance in Table II. One can see that the signal-to-background ratios deteriorate when the energy of collisions increases, simply because the backgrounds outgrow the signal rapidly. The significance levels that we can achieve are not as good as those at the Tevatron. Unless the systematic uncertainties can be controlled to the level of 2%, the observability at the LHC would be hard.

VI. USING THE $Z' \to b\bar{b}$ MODE AT THE LHC AND THE TEVATRON

Improvement can be made if the Z' boson decays into $b\bar{b}$, because both CMS and ATLAS experiments have a decent B-tagging efficiency and a rather low mistag probability [27]. To make the analysis simple enough but still semi-realistic we choose the B-tagging and mistag efficiencies to be

$$\epsilon_b \approx 0.5, \quad \epsilon_{\text{mistag}} = 0.01 \; . \tag{26}$$

We assume the $b\bar{b}$ branching ratio of the Z' to be

$$B(Z' \to b\bar{b}) = 0.15 \; , \tag{27}$$

where this choice is close to the democratic choice and at the same time consistent with the dedicated $\ell\nu b\bar{b}$ search [28] at the Tevatron. The cuts on the b-quark jets, leptons, and photons are the same as those presented in the last section.

We show the cross sections and significance at the LHC in Table III. We can see that the backgrounds decrease substantially, because the regular jets are dominated by gluons and light quarks. When one demands b quarks, it decreases tremendously. On the other hand, the signal is only down by a factor $B(Z' \to b\bar{b})$ here. Then both the signal and background are subject to the B-tagging efficiency. The signal-to-background ratios improve significantly in all channels: especially $Wb\bar{b} \to \ell\nu b\bar{b}$ has the ratio larger than 1. Even with an easy systematic uncertainty of 10% and at 7 TeV with only 1 fb^{-1}, the $Wb\bar{b}$ channel is very

TABLE II. Signal and background cross sections for $\gamma Z' \to \gamma jj$, $ZZ' \to \ell^+\ell^- jj$, $ZZ' \to \nu\bar{\nu}jj$, and $WZ' \to \ell\nu jj$ at the LHC (7, 10, 14 TeV) for $M_{Z'} = 150$ GeV, with jet cuts defined in Eqs. (22). Photons cuts for γjj are in Eq. (23), the lepton cuts are in Eq. (24) and in Eq. (25). Significance levels are calculated with 10%, 6%, and 2% systematic uncertainty, shown in the last three columns, respectively, with the corresponding luminosity $\mathcal{L}$.

LHC	$\sigma_{\rm signal}$	$\sigma_{\rm bkgd}$	$\frac{S}{\sqrt{B}\oplus 0.1B}$	$\frac{S}{\sqrt{B}\oplus 0.06B}$	$\frac{S}{\sqrt{B}\oplus 0.02B}$
	$\gamma Z' \to \gamma jj$				
7 TeV (1 fb^{-1})	0.83 pb	40.9 pb	0.20	0.34	0.99
10 TeV (10 fb^{-1})	1.2 pb	66.6 pb	0.18	0.31	0.91
14 TeV (100 fb^{-1})	1.7 pb	104.2 pb	0.16	0.27	0.82
	$ZZ' \to \ell^+\ell^- jj$ ($\ell = e, \mu$)				
7 TeV (1 fb^{-1})	0.051 pb	0.72 pb	0.66	1.0	1.7
10 TeV (10 fb^{-1})	0.081 pb	1.27 pb	0.64	1.1	2.9
14 TeV (100 fb^{-1})	0.12 pb	2.08 pb	0.58	0.96	2.9
	$ZZ' \to \nu\bar{\nu}jj$ ($\nu = \nu_e, \nu_\mu, \nu_\tau$)				
7 TeV (1 fb^{-1})	0.28 pb	4.92 pb	0.56	0.92	2.3
10 TeV (10 fb^{-1})	0.46 pb	9.16 pb	0.50	0.84	2.5
14 TeV (100 fb^{-1})	0.70 pb	15.6 pb	0.45	0.75	2.2
	$WZ' \to \ell\nu jj$ ($\ell = e, \mu$)				
7 TeV (1 fb^{-1})	0.36 pb	4.75 pb	0.75	1.2	3.1
10 TeV (10 fb^{-1})	0.57 pb	8.45 pb	0.67	1.1	3.3
14 TeV (100 fb^{-1})	0.84 pb	13.8pb	0.61	1.0	3.0

feasible. On the other hand, the $\gamma b\bar{b}$ channel needs a better systematic uncertainty in order to be observed, and the $Zb\bar{b} \to (\ell^+\ell^-/\nu\bar{\nu})b\bar{b}$ needs more luminosity. In conclusions, the search using $Z' \to b\bar{b}$ is far better than regular jets, provided that $B(Z' \to b\bar{b}) > 0.1$.

One may wonder if using $Z' \to b\bar{b}$ mode at the Tevatron would also be useful. We repeat the exercise for the Tevatron and list the signal and background cross sections and significance in Table IV. Note that we require to have double B-tags and that is the reason why the background is reduced so significantly from those shown in Table I. The signal is

TABLE III. Signal and background cross sections for $\gamma Z' \to \gamma b\bar{b}$, $ZZ' \to \ell^+\ell^- b\bar{b}$, $ZZ' \to \nu\bar{\nu}b\bar{b}$, and $WZ' \to \ell\nu b\bar{b}$ at the LHC (7, 10, 14 TeV) for $M_{Z'} = 150$ GeV, with jet cuts defined in Eqs. (22). Photons cuts for $\gamma b\bar{b}$ are in Eq. (23), the lepton cuts for $Zb\bar{b} \to \ell^+\ell^- b\bar{b}$ and $Wb\bar{b} \to \ell\nu b\bar{b}$ channels are in Eq. (24) and in Eq. (25). We have assumed B-tagging and mistag efficiencies as in Eq. (26) and branching ratio $B(Z' \to b\bar{b}) = 0.15$. Significance levels are calculated with 10%, 6%, and 2% systematic uncertainty, shown in the last three columns, respectively.

LHC	σ_{signal}	σ_{bkgd}	$\frac{S}{\sqrt{B} \oplus 0.1B}$	$\frac{S}{\sqrt{B} \oplus 0.06B}$	$\frac{S}{\sqrt{B} \oplus 0.02B}$
	$\gamma Z' \to \gamma b\bar{b}$				
7 TeV (1 fb^{-1})	0.031 pb	0.083 pb	2.5	3.0	3.3
10 TeV (10 fb^{-1})	0.046 pb	0.16 pb	2.8	4.5	9.1
14 TeV (100 fb^{-1})	0.064 pb	0.28 pb	2.3	3.8	11.0
	$ZZ' \to \ell^+\ell^- b\bar{b}$ $(\ell = e, \mu)$				
7 TeV (1 fb^{-1})	0.0019 pb	0.0031 pb	1.1	1.1	1.1
10 TeV (10 fb^{-1})	0.0030 pb	0.0065 pb	2.9	3.4	3.7
14 TeV (100 fb^{-1})	0.0045 pb	0.012 pb	3.5	5.5	10.4
	$ZZ' \to \nu\bar{\nu}b\bar{b}$ $(\nu = \nu_e, \nu_\mu, \nu_\tau)$				
7 TeV (1 fb^{-1})	0.011 pb	0.017 pb	2.4	2.5	2.5
10 TeV (10 fb^{-1})	0.017 pb	0.037 pb	4.1	5.9	8.4
14 TeV (100 fb^{-1})	0.026 pb	0.071 pb	3.7	6.0	15.9
	$WZ' \to \ell\nu b\bar{b}$ $(\ell = e, \mu)$				
7 TeV (1 fb^{-1})	0.014 pb	0.0047 pb	6.1	6.2	6.2
10 TeV (10 fb^{-1})	0.021 pb	0.0074 pb	18.9	22.1	24.5
14 TeV (100 fb^{-1})	0.032 pb	0.011 pb	27.4	42.6	79.1

only reduced by the branching ratio $B(Z' \to b\bar{b})$ and the double B-tagging efficiency. We only show the significance levels with 10% systematic uncertainty, because the significance levels are high enough that one should be able to see the excess. According to the significance only, the $WZ' \to \ell\nu b\bar{b}$ with double B-tagging is the most promising channel to probe this baryonic Z' boson. Considering the statistically large enough events, $\gamma Z' \to \gamma b\bar{b}$ is also very favorable.

TABLE IV. Signal and background cross sections for $\gamma Z' \to \gamma b\bar{b}$, $ZZ' \to \ell^+\ell^- b\bar{b}$, $ZZ' \to \nu\bar{\nu}b\bar{b}$, and $WZ' \to \ell\nu b\bar{b}$ at the Tevatron for $M_{Z'} = 150$ GeV, with b-jet cuts defined in Eqs. (18) and (21). Photons cuts for $\gamma b\bar{b}$ are in Eq. (20), the lepton cuts for $Zjj \to \ell^+\ell^- jj$ are in Eq. (19), and the leptonic cuts for $Wjj \to \ell\nu jj$ are $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 1$, and $\not{E}_T > 25$ GeV. The B-tagging and mistag efficiencies are as in Eq. (26) and branching ratio $B(Z' \to b\bar{b}) = 0.15$. Significance levels are calculated with 10% systematic uncertainty and $\mathcal{L} = 10$ fb^{-1}.

b-Jet cuts (Tevatron)	σ_{signal}	σ_{bkgd}	$\frac{S}{\sqrt{B}\oplus 0.1B}$
	$\gamma Z' \to \gamma b\bar{b}$		
$E_{Tb} > 30$ GeV	18.4 fb	22.5 fb	6.8
$E_{Tb} > 50$ GeV	10.5 fb	10.3 fb	7.3
	$ZZ' \to \ell^+\ell^- b\bar{b}$ $(\ell = e, \mu)$		
$E_{Tb} > 30$ GeV	0.97 fb	0.59 fb	3.9
$E_{Tb} > 50$ GeV	0.56 fb	0.30 fb	3.2
	$ZZ' \to \nu\bar{\nu}b\bar{b}$ $(\nu = \nu_e, \nu_\mu, \nu_\tau)$ with $\not{E}_T > 40$ GeV		
$E_{Tb} > 30$ GeV	4.5 fb	4.1 fb	5.9
$E_{Tb} > 50$ GeV	2.7 fb	1.5 fb	6.5
	$WZ' \to \ell\nu b\bar{b}$ $(\ell = e, \mu)$		
$E_{Tb} > 30$ GeV	6.0 fb	2.4 fb	11
$E_{Tb} > 50$ GeV	3.6 fb	1.3 fb	9.3

VII. CONCLUSIONS

In summary, we have shown that a baryonic Z' boson can explain the excess in the invariant-mass window $130 - 170$ GeV in the dijet system of Wjj production. Such a Z' boson without leptonic couplings is not subject to the current dilepton limits on extra gauge bosons. Yet, the strongest constraint comes from the dijet search of the UA2 data, from which the size of coupling, proportional to $\sqrt{\lambda}$, is constrained to be $\lambda \lesssim 1$. With $\lambda = 1$ we are able to explain the required cross section of 4 pb in the excess window. We have also shown that it is hard to see the excess in $\gamma Z' \to \gamma jj$ and $ZZ' \to \ell^+\ell^- jj$ channels at the Tevatron under the current systematic uncertainties and jet cuts. However, with tightened jet cuts and improved systematic uncertainties it could be promising to test the excess in

these two channels.

The situation at the LHC with $\sqrt{s} = 7, 10, 14$ TeV does not improve because the backgrounds grow with energy much faster than the signal. The signal-to-background ratios drop and so do the significance levels. On the other hand, we have shown that if $B(Z' \to b\bar{b}) > 0.1$ we can use the $\gamma b\bar{b}$, $Zb\bar{b}$, and $Wb\bar{b}$ channels and the observability improves substantially at the LHC. In particular, the $Wb\bar{b} \to \ell\nu b\bar{b}$ mode has a signal-to-background ratio larger than 1 and very high significance levels. We urge the LHC experimenters to search for the $WZ' \to \ell\nu b\bar{b}$ as well.

A similar urge is also applicable to the Tevatron. We have shown that the $WZ' \to \ell\nu b\bar{b}$, $\gamma Z' \to \gamma b\bar{b}$, and $ZZ' \to \nu\bar{\nu} b\bar{b}$ channels are observable with the present level of uncertainties.

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